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COMPARISON OF ROAD LOAD SIMULATOR TEST RESULTS WITH TRACK

TESTS ON ELECTRIC VEHICLE PROPULSION SYSTEM

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SUMMARY

A special-purpose dynamometer, the road load simulator, is being used at NASA's Lewis Research Center to test and evaluate electric vehicle propulsion systems under DOE's Electric and Hybrid Vehicle Program. The RLS provides tire resistance and aerodynamic loads that duplicate road conditions. Inertial loads are simulated with flywheels. Track tests were performed on the Lewis electric propulsion system test vehicle at the Transportation Research Center of Ohio. Similar tests were conducted on the identical propulsion system on the RLS. This report compares the results of both sets of tests and discusses some of the factors that affect the track test results.

The two predominant factors that create scatter in track test results are the variances in the road load due to the change in tire resistance and the effect the wind has on the aerodynamic drag. Because the tires were not low-rolling-resistance tires, the internal air temperature increased significantly with the speed of the vehicle and the time driven. The rolling resistance dropped as the tire contained-air temperature increased. An increase of 22 deg C (40 deg F) can decrease the tire resistance by 18 percent.

Wind effects are difficult to evaluate because, by nature, the wind occurs in gusts of varying magnitude and direction. Wind gusts of 16 km/hr (10 mph) can cause variations in road load of 29 percent. The measured value can differ greatly at different locations on the track.

On the other hand the tests conducted on the road load simulator were at a fixed value of tire rolling resistance and fixed aerodynamic drag. As a result the scatter in the RLS data was very small.

Agreement between the two sets of test results was quite good, however. A comparison was made between motor current times motor voltage required to maintain a constant vehicle speed for fixed throttle settings. It appears that the road load used in the RLS as determined by coastdown tests was slightly lower than the track test results indicate. This difference may have been due to variations in tire contained-air temperature.

INTRODUCTION

NASA's Lewis Research Center is using a special-purpose dynamometer to test and evaluate electric vehicle propulsion systems developed under DOE's Electric and Hybrid Vehicle Program. This road load simulator (RLS) provides tire resistance, aerodynamic drag, inertial loads, and grade loads that duplicate the loads a propulsion system would see if installed in a vehicle on the road. The RLS is described in reference 1. To better understand how RLS testing correlates with track testing, a test program was carried out on a

propulsion system installed on the RLS and on the same propulsion system in a vehicle on a test track at the Transportation Research Center of Ohio. This report compares the test results and discusses those factors that influence the test results.

VEHICLE DESCRIPTION

Selection of a vehicle and propulsion system for the correlation tests was based on the ease of instrumenting the system, the simplicity of the system, the ease of interpreting the results, and availability. The selected system uses a series dc motor with an SCR chopper and has no transmission.

The vehicle chosen for the tests was the NASA Lewis Research Center electric propulsion system test vehicle (fig. 1). In 1976, when the vehicle was built, the propulsion system was representative of available systems for electric vehicles. The propulsion system, including the motor, controller, and differential, was removed from the vehicle for the RLS installation (fig. 2) after the track tests.

The Lewis electric propulsion system test vehicle was built to evaluate electric vehicle propulsion systems on the road. The front-wheel-drive vehicle was built from the ground up by the Electric Vehicle Engineering Co. (EVE) of Boston, Massachusetts, using chassis parts from existing vehicles where possible.

Motor

The motor was manufactured by Northwestern Electric Company of Chicago, Illinois. It is a four-pole machine with a series field winding. The continuous duty output power rating is 14.9 kW (20 hp). The motor was thoroughly tested previously by Lewis to study the effects of chopper control on dc motor performance. The results of this study are reported in reference 2.

Controller

The controller, a Pulsomatic Mark 10 furnished by Cableform Incorporated of Troy, Virginia, provides infinitely variable control of a dc series-wound motor. A simplified diagram of the controller is shown in figure 3.

Differential

The motor is coupled directly to the differential as there is no transmission in the vehicle. The differential ratio is 5.17. The vehicle and its propulsion system are described in more detail in reference 3.

INSTRUMENTATION

Test Track Instrumentation

The vehicle was instrumented to accomplish the following objectives:

- (1) To determine tire and aerodynamic characteristics for programming the RLS
- (2) To obtain performance data on the vehicle that could be compared with data from similar tests on the RLS

Tire contained-air temperature and vehicle speed were measured during coast-down and towing tests to accomplish the first objective. Motor and battery current, motor and battery voltage, and vehicle speed were recorded during vehicle performance tests. All measurements were recorded simultaneously on three Honeywell 195 Electronik two-channel strip-chart recorders, which have an accuracy of ± 0.5 percent of full scale. A schematic of the vehicle instrumentation is shown in figure 4. The battery current was measured with an 0- to 400-A coaxial shunt that is within ± 0.1 percent of full scale. Vehicle speed was measured with a Labeco NC-7 fifth wheel. Accuracy of the fifth wheel as verified with a Kustom Electronics Model HR8 radar gun was estimated to be ± 1.6 km/sec (± 1.0 mph).

RLS Test Instrumentation

The variables used to make comparisons were battery current, using the same current shunt as was used during the track tests, battery voltage, and vehicle speed as determined by the differential axle speed. In addition, power between each component was determined by using torque and speed measurements for the motor and differential outputs and by using wattmeters for the battery and controller outputs. The accuracy of the torque transducer is ± 0.25 percent of full scale, and the accuracy of the wattmeter is ± 0.4 percent of full scale. Temperatures of the batteries, motor, and differential were also measured. A schematic of the instrumentation locations on the propulsion system is shown in figure 5.

TEST PROCEDURES

Results of tests conducted on an electric vehicle propulsion system in the RLS were compared with similar tests on the same propulsion system installed in a vehicle and tested on a track. The vehicle road load as measured on the track was programmed into the RLS. The track slope was also duplicated on the RLS.

Track Test Procedure

The track tests were conducted on the 12-km (7.5-mile) continuous-loop test track at the Transportation Research Center located at East Liberty, Ohio. The track, vehicle preparation, and details of the individual run procedures are described in detail in reference 3. Note that the two straight sections of the track have grades of ± 0.228 percent in the south to north

direction and -0.228 percent in the north to south direction. All data presented in this report were taken on the straight sections.

The track tests were run with the throttle blocked so that a constant throttle position was maintained for at least one lap of the track. A typical recorder chart of vehicle speed and motor current is shown in figure 6. Note that the vehicle speed varied depending on whether the vehicle was on the +0.228-percent-grade portion of the track or on the -0.228-percent-grade portion. In this example the difference in speed was 8 km/hr (5 mph). The motor current went down as the speed went up on the -0.228-percent grade even though the throttle was blocked and its position remained constant. On the +0.228-percent grade the speed went down and the motor current went up. The blocked-throttle tests were repeated at several throttle settings and resulted in vehicle speeds to 72 km/hr (45 mph). From the blocked-throttle test results, plots of battery current times battery voltage as a function of vehicle speed were prepared. Battery current times battery voltage was chosen as the comparison variable to compensate for voltage deviations that occur for various battery states of charge.

RLS Test Procedure

The entire propulsion system was removed from the vehicle and installed on the RLS. The differential was locked up so that it could connect into the RLS by only one axle shaft. The RLS was set up to produce road loads equivalent to those seen by the vehicle during the track tests. The road load equation is

$$F = 9.807 W f_1 + 0.0437 C_d A V^2 + 9.807 W \sin \left(\tan^{-1} \frac{\text{Grade}}{100} \right) \quad (\text{in SI units})$$

$$F = W f_1 + 0.00235 C_d A V^2 + W \sin \left(\tan^{-1} \frac{\text{Grade}}{100} \right) \quad (\text{in U.S. customary units})$$

where

- F road load, N (lb)
- W vehicle weight, kg (lb)
- V vehicle velocity, km/hr (mph)
- C_d aerodynamic drag coefficient
- A vehicle cross-sectional area, m^2 (ft^2)
- f_1 tire rolling resistance, kg/kg of vehicle weight (lb/lb of vehicle weight)

The values used for tire rolling resistance were determined by tests conducted at the test track.

Aerodynamic drag was determined from coastdown tests on the vehicle by using the procedure developed by White and Korst (ref. 4). Ten coastdowns were conducted - five in each direction - on the track. The average value of aerodynamic drag coefficient times vehicle cross-sectional area ($C_d A$) for 10 trials was 0.421 m^2 (4.53 ft^2). The average value for each of the five pairs of runs (one in each direction) varied from 0.388 m^2 (4.18 ft^2) to 0.454 m^2 (4.89 ft^2). This then was the value used to program the RLS.

The tire rolling resistance was determined from towing tests. The procedure for the towing test is presented in detail in reference 5. The value used for tire resistance, which includes bearing friction and brake drag, was 0.0135 kg/kg of vehicle weight. The road load is shown in figure 7 for both +0.228-percent grade and -0.228-percent grade.

The road load simulator was programmed to duplicate the track road load as determined in the previous section. The flywheel weight was set for 1514 kg (3330 lb), which is the closest available weight increment to the actual test weight of the vehicle, 1505 kg (3310 lb). Steady-state tests were run by setting the throttle for speeds of 8.0, 16.1, 24.1, 32.2, 40.2, 48.3, 56.3, and 64.4 km/hr (5, 10, 15, 20, 25, 30, 35, and 40 mph) on grades of +0.228 and -0.228 percent. The input power was supplied by a large motor-generator set. The voltage was regulated to be the same as the battery voltage observed during the track tests for identical vehicle speeds and road load conditions. The output of the motor-generator set was filtered to furnish steady dc current. Additional compensation for varying battery voltage was provided by comparing battery current times battery voltage instead of battery current alone.

TEST RESULTS

The battery current times battery voltage is plotted as a function of vehicle speed for the propulsion system tested at the track in figure 8. The +0.228-percent-grade data are shown in figure 8(a) and the -0.228-percent-grade data are shown in figure 8(b). A second-order least-squares fit to the experimental data is shown in figure 8. Because of noise developed by the chopper in the tire contained-air temperature signal, tire temperature was not recorded during the comparison tests.

In figure 9 the RLS data have been plotted over the least-squares fit to the track data; the +0.228-percent-grade data in figure 9(a) and the -0.228-percent-grade data in figure 9(b).

DISCUSSION OF RESULTS

The RLS test results were generally in good agreement with the track data. At the lower vehicle speeds the road load used in the RLS appears to be slightly lower than the track test results would indicate. All of the RLS tests were run with a fixed tire resistance value of 0.0135 kg/kg of vehicle weight as an average value over the entire speed range. This corresponds with a tire contained-air temperature of 41° C (105° F). During the track tests the tire contained-air temperature varied from 23° to 52° C (73° to 126° F). Tire resistance during the track tests varied because of the tire contained-air temperature effect on tire resistance. Factors affecting the tire contained-air temperature include vehicle speed, ambient temperature, sunlight, and the time of day. Therefore it is very likely that some of the difference between the RLS test results and the track test results was due to the variation in tire temperature during the track tests. From the values of road load at the higher speeds it appears that the value used for the aerodynamic drag coefficient was about 10 percent lower than the actual track test

results would indicate. There was not sufficient time left in the program to investigate this further.

Many factors contribute to duplicating track test results on a dynamometer such as the RLS. Most of these factors are beyond the control of the experimenter. Because the track tests had to be conducted during a given time frame, the tests were run during a variety of air temperature, wind, and solar radiation conditions. Table I lists the wind and ambient-temperature conditions during the tests. Tests on special electric vehicle tires conducted during the same time frame as the tests described in this report determined that the largest influence on tire resistance was solar heating.

To determine the effect of atmospheric conditions, only the terms of the road load equation that represent tire rolling resistance and aerodynamic drag were considered. The effect of a steady 16-km/hr (10-mph) wind on the aerodynamic drag term, $0.0437 C_d A V^2$ ($0.00236 C_d A V^2$), was considered. The difference in force when driving with the wind and against the wind was

$$\Delta F = 0.0437 C_d A (v_1^2 - v_2^2), \text{ N}$$

or

$$\Delta F = 0.00236 C_d A (v_1^2 - v_2^2), \text{ lb}$$

where

V_1 sum of vehicle and wind velocities, km/hr (mph)
 V_2 difference in vehicle and wind velocities, km/hr (mph)

If the vehicle velocity was 64 km/hr (40 mph), the difference in road load between driving with and against the wind was 76.06 N (17.1 lb). This resulted in a difference in axle torque of 22.60 N-m (200 lb-in). At 64 km/hr (40 mph) this represents a 29 percent difference in road load. This example is meant only to help explain some of the scatter observed in the track data and can in no way be used to correct the data. The wind values listed in the table were observed at the weather station at the TRC facility and cannot be assumed for any other portion of the track because of the gusty nature of the wind and the elevation of the anemometer and because certain portions of the track seemed to intensify the wind while other portions of the track were protected from the wind. Also, the wind was seldom aligned with the vehicle's longitudinal axis.

The other factor that greatly affects the road load on a track surface or highway is the tire temperature, or more precisely, the effect that tire temperature has on the tire rolling resistance. Although the tires used during these tests were radial tires, they were not specially designed for low rolling resistance. The resistance was higher than that observed for the low-rolling-resistance tires used in the tests of reference 5, and of equal importance the tire temperature was more affected by vehicle speed, probably because of heavier sidewalls. Of course, this effect lowers the rolling resistance at higher speeds if the time at speed is long enough. The tire steady-state rolling resistance as a function of tire contained-air temperature is shown in figure 10. This relationship was determined by towing the

vehicle at low speed and measuring the force with a load cell. The procedure is explained in detail in reference 5.

The comparison tests were all started with the tires at near atmospheric temperature. Since only two laps of the track were traversed for each test, the tires did not reach equilibrium temperatures. Previous tests showed that the tires require up to 60 min to reach equilibrium temperature, depending on vehicle speed. From figure 10 it can be seen that for a contained-air temperature of 27° to 49° C (80° to 120° F) the tire rolling resistance will change from 0.0152 to 0.0125 kg/kg of vehicle weight. This represents an 18 percent variation in the tire rolling resistance term of the road load equation.

CONCLUDING REMARKS

Comparison tests were conducted on an electric vehicle propulsion system both in a vehicle on a test track and out of the vehicle on the RLS dynamometer. These tests brought out some of the factors that create more uncertainty and scatter in the results of track tests than has been observed during dynamometer tests.

It was shown that variations in road load due to wind gusts up to 16 km/hr (10 mph) caused total road load variations of 29 percent at 64 km/hr (40 mph). The wind gust factor apparently caused much of the data scatter.

Another factor to be considered is the variation in rolling resistance of the tires with contained-air temperature. A temperature change of 27 to 49 deg C (80 to 120 deg F) caused an 18 percent change in the tire rolling resistance term of the road load equation. The tire contained-air temperature variation was larger for the tires used in these comparison tests than was observed with special low-rolling-resistance tires.

The variations in road load observed on the test track are more representative of "real world" conditions, and vehicle performance tests conducted under these conditions more closely represent performance on the road. However, when the test results are to be compared with those of other systems tested under similar circumstances, carefully controlled dynamometer tests will result in more consistent comparisons.

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TABLE I. - AMBIENT CONDITIONS DURING TRACK TESTS

Run	Date	Test speed		Wind			Ambient temperature	
		km/hr	mph	Direction ^a , deg	Velocity		°C	°F
					km/hr	mph		
93	7-10-81	68-72	42-45	78-360	6-10	4-6	24	75-76
94	7-10-81	64-69	40-43	18-360	8-11	5-7	26	78-79
99	7-14-81	34-42	21-26	18-352	5-16	3-10	27	80-81
101	7-15-81	58-63	36-39	115-198	3-8	2-5	24	75-76
102	7-15-81	58-64	36-40	9-110	3-10	2-6	24-27	76-80
105	7-16-81	58-66	36-41	45-90	3-6	2-4	26-27	78-80
106	7-16-81	37-45	23-28	315-324	2-8	1-5	26-27	78-80
107	7-16-81	43-53	27-33	333-350	2-8	1-5	26	78
113	7-21-81	48-56	30-35	279-360	6-16	4-10	24-26	76-78
115	7-22-81	32-39	20-24	18-360	3-6	2-4	17-19	63-66
116	7-22-81	50-55	31-34	36-306	2-6	1-4	19	66-67
117	7-22-81	40-43	25-27	351-360	3-10	2-6	20-21	68-69
123	8-11-81	11-16	7-10	270	16-24	10-15	24-26	76-78
124	8-11-81	26-32	16-20	252-279	8-24	5-15	25-26	77-78
127	8-12-81	13-21	8-13	243-279	6-19	4-12	26	78-79
128	8-12-81	26-37	16-23	252-270	10-19	6-12	26-27	78-80
131	8-13-81	23-29	14-18	252-270	8-16	5-10	27-28	80-82
134	8-13-81	42-47	26-29	198-270	8-19	5-12	27	80

^aTrack orientation, 330°/150°.

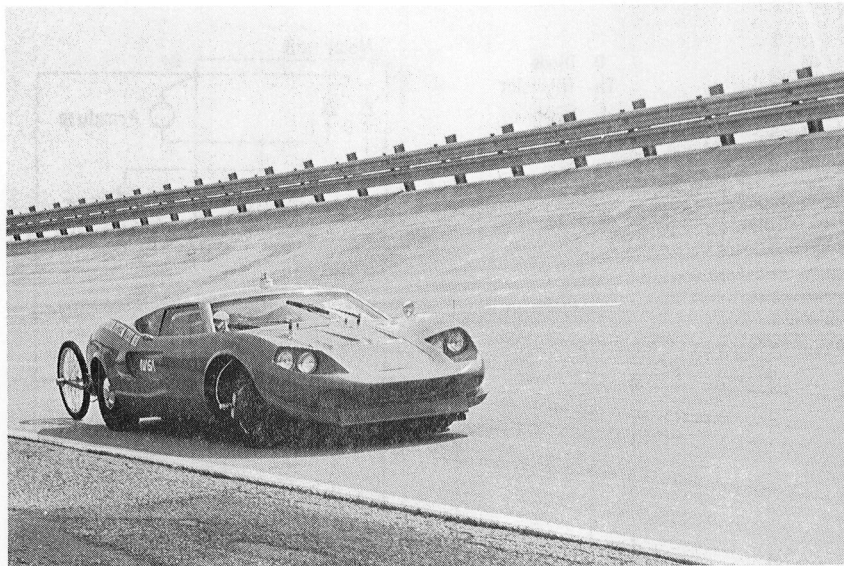
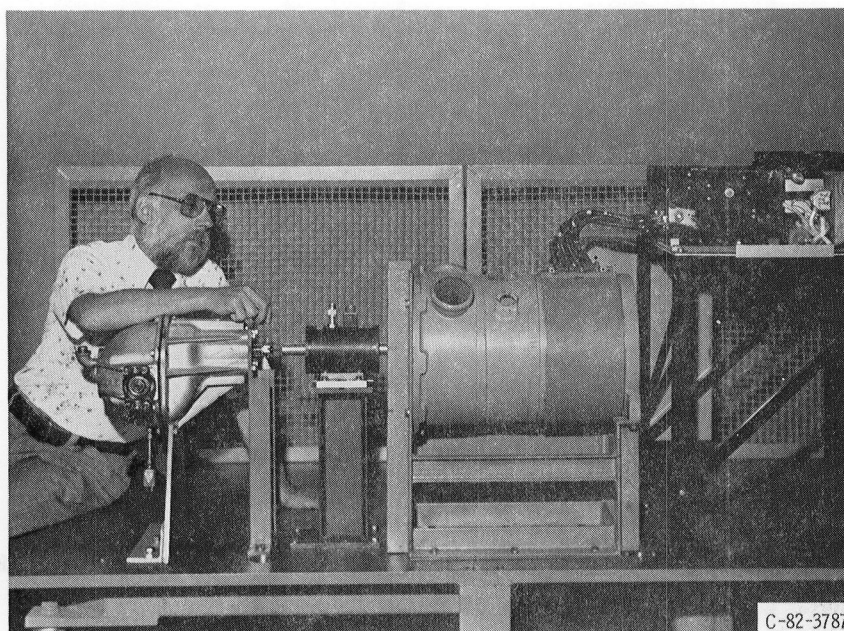


Figure 1. - Electric propulsion system test vehicle.



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Figure 2. - Propulsion system from electric propulsion system test vehicle mounted on road load simulator.

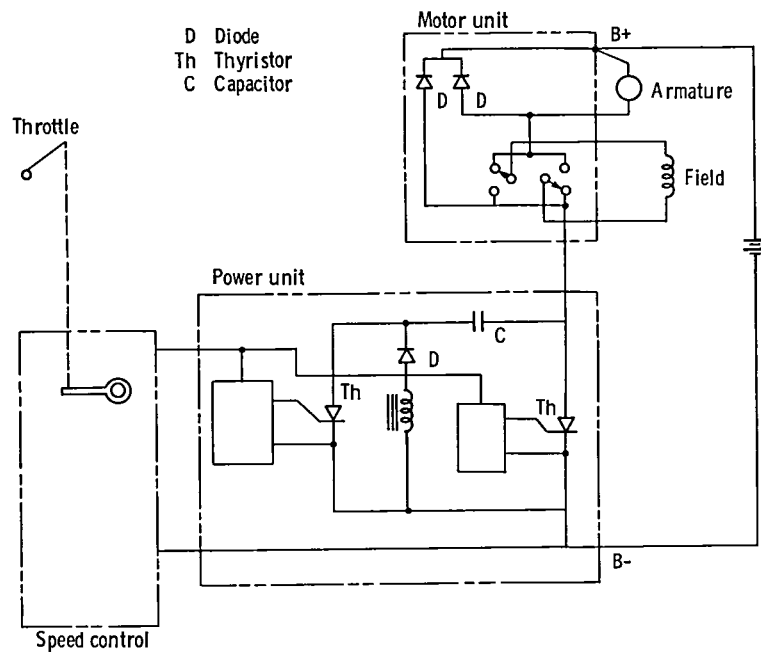


Figure 3. - Schematic diagram of controller.

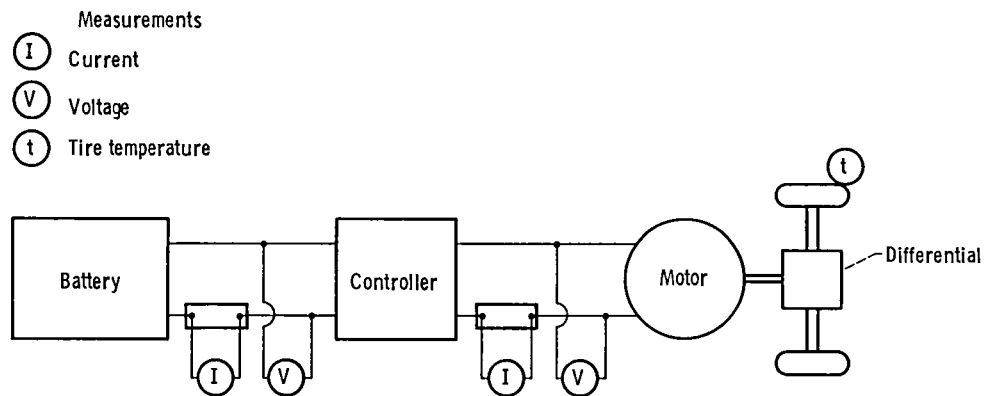


Figure 4 - Instrumentation for track tests.

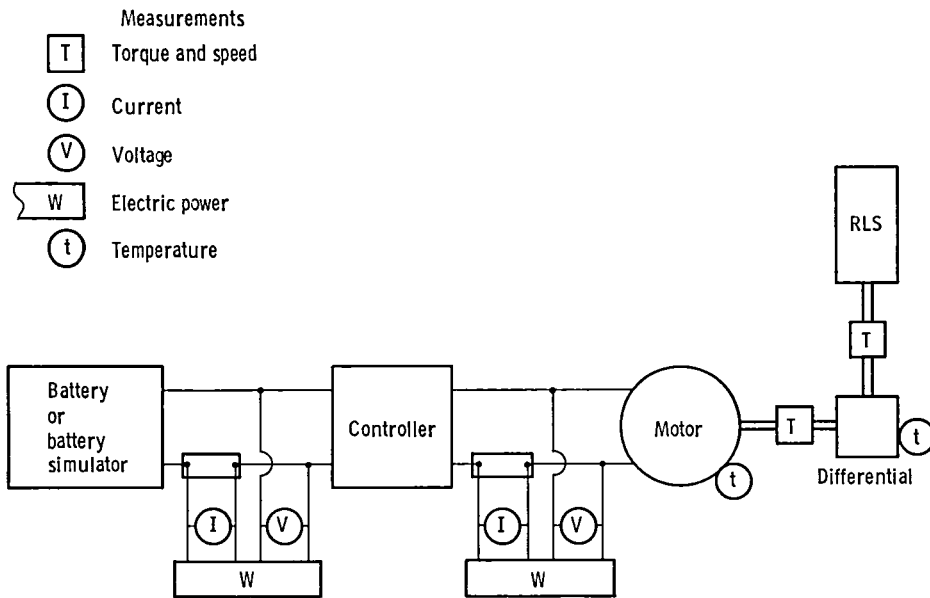


Figure 5. - Instrumentation for RLS tests.

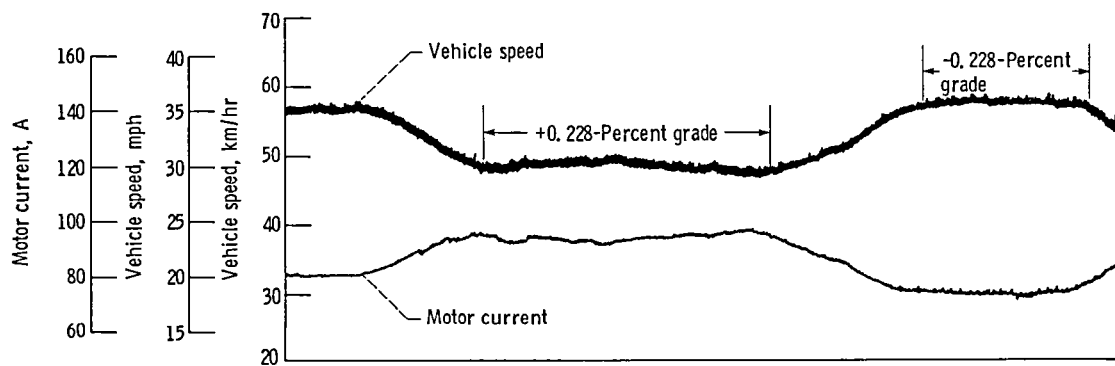


Figure 6. - A typical recorder chart showing speed and motor current.

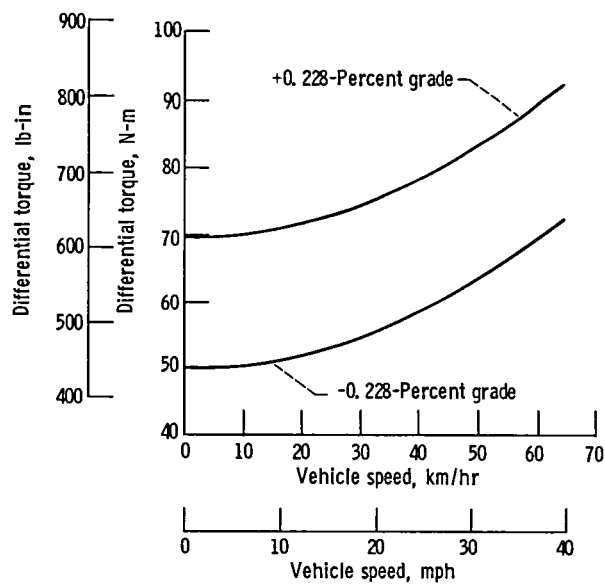


Figure 7. - Road load as a function of vehicle speed for both +0.228-percent and -0.228-percent grades.

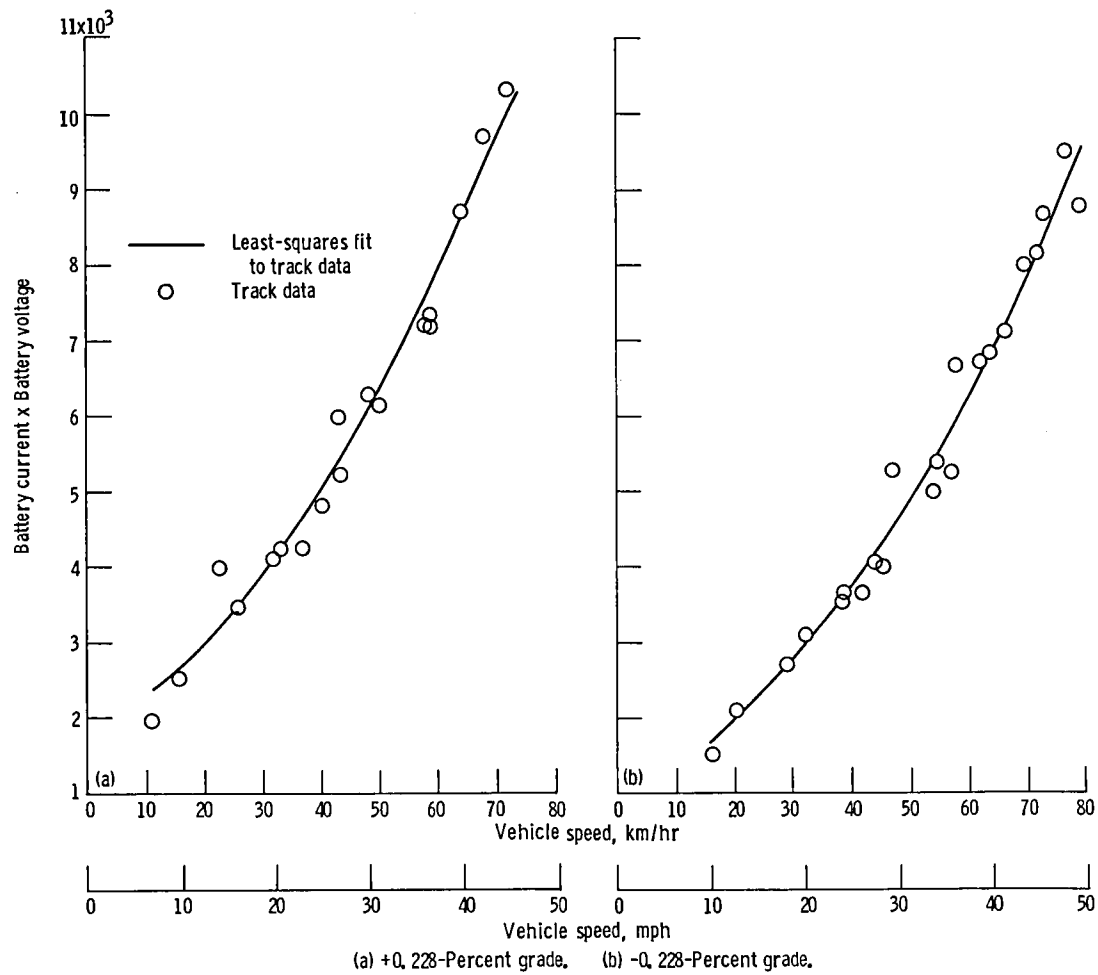
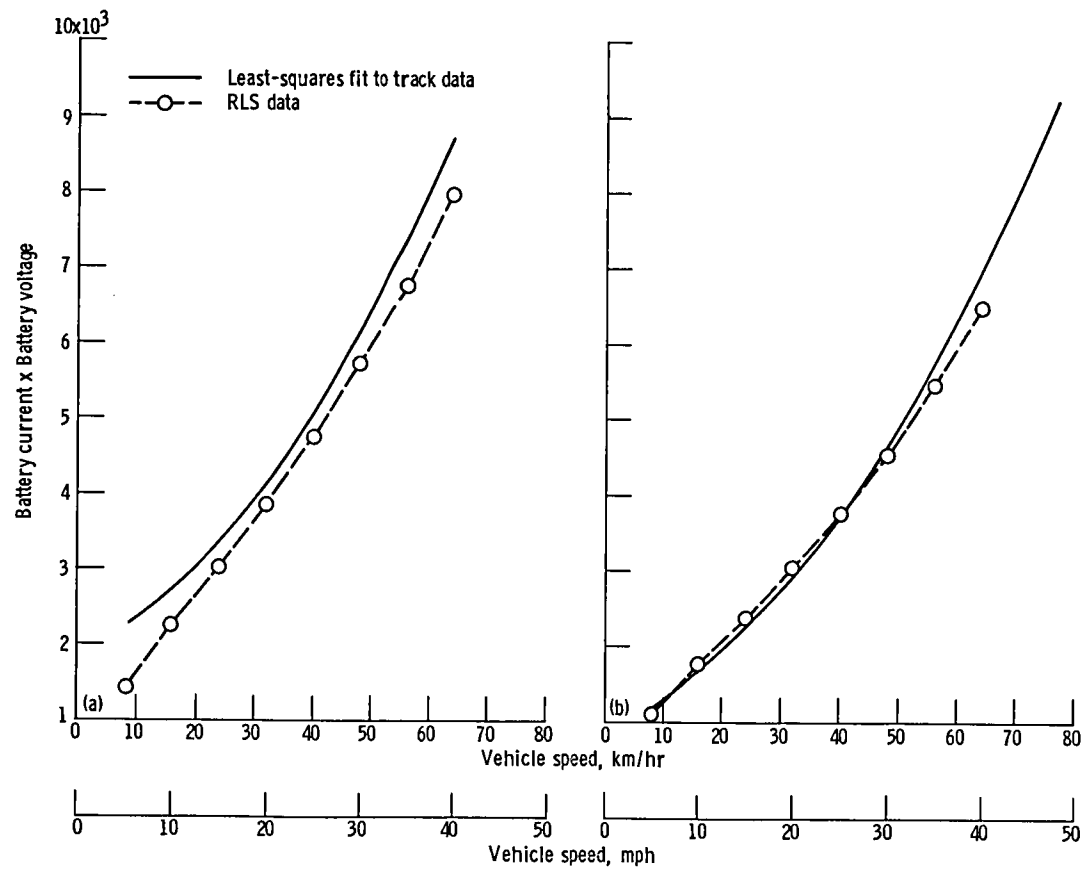


Figure 8. - Battery current times battery voltage as a function of vehicle speed for blocked-throttle tests.



(a) +0.228-Percent grade. (b) -0.228-Percent grade.

Figure 9. - Comparison of RLS performance test results with similar results from track tests with vehicle.

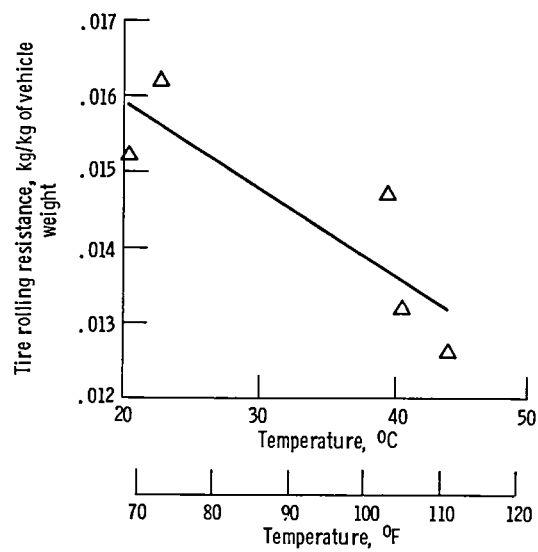


Figure 10. - Tire rolling resistance as function of tire contained-air temperature.

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16. Abstract A special-purpose dynamometer, the road load simulator (RLS), is being used at NASA's Lewis Research Center to test and evaluate electric vehicle propulsion systems developed under DOE's Electric and Hybrid Vehicle Program. To improve correlation between system tests on the RLS and track tests, similar tests were conducted on the same propulsion system on the RLS and on a test track. These tests are compared in this report. Battery current to maintain a constant vehicle speed with a fixed throttle was used for the comparison. Scatter in the data was greater in the track test results. This is attributable to variations in tire rolling resistance and wind effects in the track data. It also appeared that the RLS road load, determined by coastdown tests on the track, was lower than that of the vehicle on the track. These differences may be due to differences in tire temperature.					
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